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Prototype and Evaluation of Communication Network for a WAMPAC System Based on International Standards

by

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SUMMARY

The Wide Area Monitoring, Protection and Control (WAMPAC) system has drawn attention with the increasing introduction of smart grids and is anticipated to enhance power transmission efficiency and help cope with power system anomalies and outages. While Japanese utilities have many installations and operational experience of the WAMPAC system, the technologies used are legacy and dedicated in nature. It is thus important to apply international standards and off-the-shelf technologies to ensure the WAMPAC system becomes widely available. The authors proposed a WAMPAC system based on international standards. This paper describes its architecture and an evaluation of its prototype. The proposed WAMPAC system comprises intelligent electronic devices (IEDs), phasor measurement units (PMUs) and central equipment (CE) interconnected by Layer 2/Layer 3 (L2/L3) switch-based IP networks in cooperation with IEEE 1588 time synchronization devices. Voltage and current values sampled simultaneously or time-stamped are transmitted from the PMUs to the CE. The CE then analyzes the power system situations based on the data collected from PMUs and supervisory control and data acquisition (SCADA) system, and generates control scenarios taking account of assumed faults. When a fault occurs, IEDs make a decision to trip after analyzing the data from PMUs according to the control scenarios delivered by the CE in advance or after the fault. The proposed system can promptly respond to changes in power system situations because there is no extra process by the CE making tripping decisions. The communication network specifications were defined in terms of function, performance, reliability and cyber security in this paper. The time synchronization characteristics were also examined for L2/L3 switches with or without IEEE 1588 schemes implemented as well as multicast/unicast schemes in IEDs to show a satisfactory synchronization error of a few microseconds. We made a WAMPAC system prototype comprising four IEDs, and determined the operating time from fault occurrence to tripping to be less than 150 milliseconds.

KEYWORDS

Wide Area Monitoring, Protection and Control, Ethernet, IP network, time synchronization, cyber security

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1. Introduction

The introduction of distributed and renewable generation has had a considerable impact on power systems due to characteristics such as fluctuating output, higher system loading and bidirectional power flow. Furthermore, there is now a strong focus on "smarter grid" i.e. flexible and adaptive power systems and more efficient use of assets. These trends have sparked concerns over possible power system instability phenomena. There have also been rapid technological developments in information and communication technology (ICT), paving the way for broadband, real-time and wide-area communication infrastructures. These advances in communications infrastructure are also becoming increasingly accessible in the field of power system protection and control. In parallel, the related communications standardization process, which is vital for the integration of components, has been the subject of discussion within international standardization bodies such as the IEC and IEEE.

Taking these trends into consideration, it is possible to mitigate the aforementioned potential power system instability phenomena cost-effectively, and expectations concerning the role of wide area monitoring, protection and control (WAMPAC) have increased [1]. Dedicated WAMPAC systems utilizing our unique approach of communicating synchronized sampled values for applications in power system stabilization have seen ongoing development and application in Japan since the 1970s [2] and the technology is well-established with 40 years of in-service experience. However, the technologies used are legacy and dedicated. Since it is important to apply international standards and off-the-shelf technologies to ensure the WAMPAC system becomes widely available, the authors proposed a WAMPAC system based on international standards [3].

This paper starts by describing the architecture of the WAMPAC system, followed by a list of communication network specifications regarding function, performance, reliability and cyber security. Next, the time synchronization schemes, one of the system's key components, are examined for Layer 2 (L2) and Layer 3 (L3) switches with or without IEEE 1588 Precision Time Protocol (PTP) [4]-based time synchronization schemes implemented as well as multicast/unicast operations in IEDs. Finally, with a WAMPAC system prototype comprising four IEDs, the operating time from fault occurrence to tripping is examined.

2. WAMPAC System Architecture

2.1 Operational Requirements and Configuration of the WAMPAC System

The WAMPAC system is defined as one capable of monitoring a power system status in real-time and capable of executing automated control actions such as generator and/or load shedding and controlling generator excitation control systems to restore the power system network to a stable condition or prevent further deterioration when an emergency condition is triggered.

The target power system phenomena that can be alleviated by WAMPAC systems, together with the required response time for their operation, are as follows:

- Transient stability phenomena (150 ms to 1 s);
- Dynamic stability phenomena (1 to 5 s);
- Overload (up to a few tens of seconds);
- Frequency balancing between supply and demand within a smart grid (up to a few tens of seconds);
- Voltage stability (up to a few minutes).

From an algorithm perspective, WAMPAC systems can be classified into three categories; a) phenomenon confirmation type, b) phenomenon assumption type (off-line or on-line model), and c) phenomenon prediction type. The proposed WAMPAC system adopts the on-line phenomenon assumption type for the following reasons: An on-line phenomenon assumption type WAMPAC system estimates state using electrical quantities from a number of pre-defined points in the power system. The WAMPAC system also periodically evaluates the stability of the power system by performing simulations for assumed faults on main transmission lines or busbars before an actual fault occurs. When the WAMPAC system identifies a potentially unstable condition, the WAMPAC system determines the generator(s) to be shed to maintain stability. The key benefit of this approach is the fact that fast control action can be executed, even for complicated target power systems, in the event the assumed fault occurs.

To achieve the above operations, we proposed a hierarchical system configuration consisting of Central Equipment (CE), WAMPAC Gateway (WAMPAC-GW), Intelligent Electronic Device(s) (IED) and Phasor Measurement Unit(s) (PMU), as shown in Fig. 1 [2]. The WAMPAC-GW conducts the communication protocol conversion and the data aggregation/segregation like a Phasor Data Concentrator (PDC). The PMUs monitor the voltage, current and power system status, and transmit those data to the CE via the WAMPAC-GW(s) and to the IED(s). The CE can also utilize power system status data from ordinary supervisory control and data acquisition (SCADA) system located in control centers. The CE estimates state via those data, determines control scenarios in the event of an instability phenomenon, and transmits them to IED(s). The IED(s) output the tripping signal(s) to the load(s), generator(s) and/or control command(s) to generator excitation control system(s) in accordance with the data collected and the control scenario.

The operational data flow is also illustrated in Fig. 1. To realize minute-order wide-area supervision and millisecond-order fault point supervision, the hierarchical system is also effective. For the minute-order wide-area supervision, the data flow is every 30 seconds in a normal state from PMUs to CE through WAMPAC-GW, as shown in solid line arrows in Fig. 1. For the millisecond-order supervision around the fault point, the data flow is among PMUs and IEDs as shown in dashed line arrows in Fig. 1 for IEDs to execute the control based on after-fault data of specific PMUs.

2.2 International Standards Relevant to the WAMPAC System

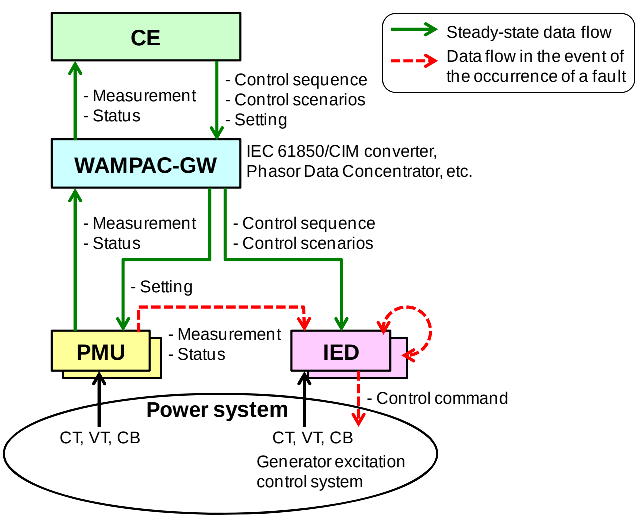


Fig. 1 Proposed WAMPAC system configuration illustrating the operational data flow

We have reviewed the standards related to WAMPAC systems in terms of the required functions and identified the key applicable standards, whether pre-existing or those currently under development as shown in Table 1.

There are no specific standards for the WAMPAC functions themselves, which depend on the target power system and operational regimes for a particular power system and differ from utility to utility.

2.3 Communication Network Specifications for the WAMPAC System

To apply the WAMPAC system to various power systems and utilities, three types of wide-area networks are considered as shown in Fig. 2. The L3/Multi-Protocol Label Switching (MPLS)-based network (Fig. 2 (a)) is most commonly applied to utility wide-area networks where other applications such as SCADA may also be accommodated. The L2-based network (Fig. 2 (b)) is presently best suited to wide-area time synchronization relevant to precise monitoring and the high-speed protection of power systems, while it is more utilized for the telecommunications industry in the form of a Provider Backbone Bridge (PBB) network than the power industry. The L2/L3 combined network (Fig. 2 (c)) is constructed by utilizing existing L3/MPLS-based networks and adding L2-based networks for high-speed and time-synchronized protection and control.

Based on our present installations and recent investigations [2-5], the generic specifications of communication networks for the WAMPAC system are summarized in Table 2 regarding communication functions, performance, reliability and cyber security.

3. WAMPAC System Performance Evaluations

3.1 Time-Synchronized Communication Networks

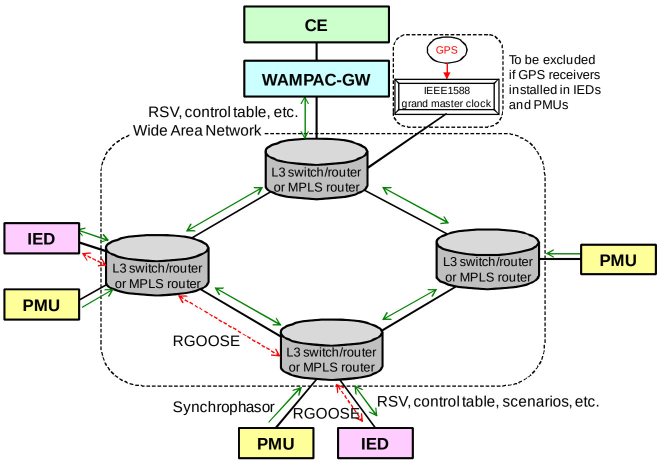
Various investigations must be conducted to meet the generic specifications shown in Table 1 for scalable wide-area communication networks. Since some applications of the WAMPAC system need wide-area time synchronization and many utilities prefer private network-based time synchronization other than GPS considering the system operability, PTP-based time synchronization performance is evaluated in this section.

Table 1 Key standards relevant to the WAMPAC system

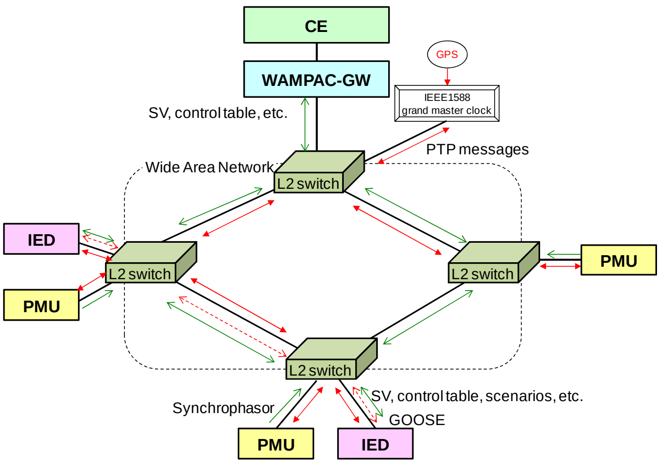
Category	Standards (Specific description)
Communication	IEEE 802.1 series for internetworking
	IETF RFC for routing and multicast
	IEC 61850-1 to 10 (Utility automation communication)
	IEC/TR 61850-90-1 (Communication between substations)
	IEC/TR 61850-90-2 (Communication between control centre and substation)
	IEC/TR 61850-90-4 (Substation LAN engineering)
	IEC/TR 61850-90-5 (Synchrophasor communication; Routable GOOSE and SV)
	IEC/TR 61850-90-12 (WAN engineering)
	IEC 61970 series (Energy management systems data and communication)
Time synchronization	IEEE 1588 (Precision Time Protocol)
	IEEE C37.238 (IEEE 1588 profile for power system)
Synchrophasor (PMU)	IEEE C37.118.1 and 2 (Synchrophasor measurement and data transfer)
	IEEE C37.244 (Phasor data concentrator)
Security	IEC/TS 62351-1 to 10 (Data and communication security for power system)
	IEC/TR 61850-90-5 (Synchrophasor communication; Security profile)

A. Internetworking of PTP time synchronization

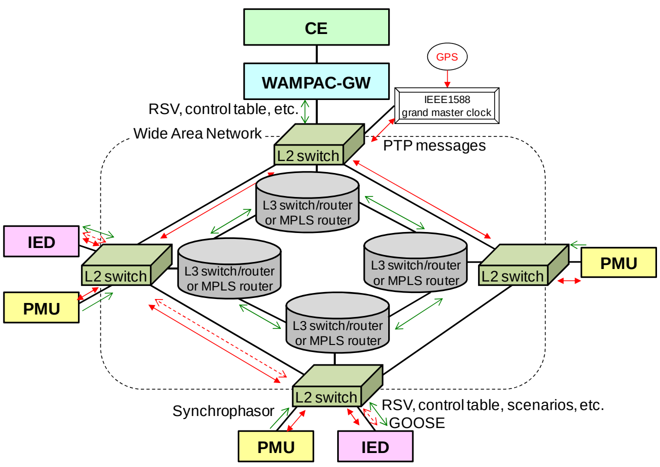
Presently, commercial PTP products are mainly supposed to utilize L2-based multicast networks, while there are two options of transmission mode, UDP and native Ethernet. When



(a) L3/MPLS-based network



(b) L2-based network



(c) L2/L3 combined network

Fig. 2 Three types of wide-area networks for the WAMPAC system

Table 2 Generic specifications of communication networks for the WAMPAC system

Item	Specification
Category	
Function	
Communication port	100 Mbps
Bandwidth	e.g. 10 Mbps for a substation with 20 IEDs
VLAN (L2-based)	One VLAN for each application with IEEE 802.1Q for LAN and IEEE 802.1ah (Provider Backbone Bridges) for WAN
Time synchronization	GPS and/or generic PTP for intra and inter substation networks with IEEE C37.238-2011 revised
Communication protocol	SV (Sample Value)/GOOSE (Generic Object Oriented Substation Event) and R-SV (Routable SV)/R-GOOSE (Routable GOOSE) for communications from and to IEDs on L2 and L3 networks, respectively. IEEE C37.118.1 for PMUs. HTTP or similar protocol for control scenario delivery by CE/WAMPAC-GW.
Multicast operation for information sharing among devices	VLAN on L2 network, and IETF RFC 4601 Protocol Independent Multicast - Sparse Mode (PIM-SM) for unidirectional multicast or IETF RFC 5015 BIDIR-PIM (Bidirectional PIM) for bidirectional multicast on L3 network
Identical bidirectional communication route	IEEE 802.1Qay Provider Backbone Bridge Traffic Engineering on L2, Traffic Engineering over MPLS, and BIDIR-PIM on L3 multicast network
Prioritized transmission	WAMPAC information prioritized from SCADA/EMS one
Performance	
Transmission delay	To meet the required response time, 3 to 5 ms among IEDs and PMUs, 1 s between IED/PMU and WAMPAC-GW/CE
Transmission delay variation	Less than a half of data sampling or transmission interval for ordinal data transmission. Less than 50 µs for time synchronization control channel, avoiding packet contention at normal communication ports.
Time synchronization error	Less than 50 µs for most stringent applications
Transmission error	Error rate less than 1×10^{-6}
Reliability	
Unavailability	Less than 3×10^{-4}, equal to teleprotection system requirement
Route assignment and redundancy	IEEE 802.1Qay and Spanning Tree Protocol (STP) or Multiple STP (MSTP) for L2 network, Traffic Engineering and Fast Reroute (FRR) for MPLS network, Open Shortest Path First (OSPF) for L3 network
Redundancy of time synchronism	BMC (Best Master Clock) or wholly redundant system applicable taking account of reliability requirements and synchronization errors of IEDs on free running mode
Cyber security	
Security management	Referring to NISTIR 7628, NIST SP 800-82, NERC CIP, etc. and based on threat analysis and risk assessment, security measures and responses applied
Availability	Defence in depth for (D)DOS attacks
Integrity	Message authentication
Confidentiality	Message encryption optionally applied taking account IED processing delays
Key management	Key management and distribution scheme defined by IEC 61850-90-5
Access control	Role Based Access Control (RBAC), user authentication, etc.
Network protection	Network separation, firewalls, intrusion detection/protection system, etc.

we implement the PTP time synchronization scheme into WAMPAC communication networks, we may have to utilize ordinary, or not PTP-implemented, L2 or L3/MPLS networks. The issue is whether ordinary networks can convey PTP synchronization messages and the time synchronization accuracy they can achieve.

We examined the internetworking of ordinary and PTP-implemented networks shown in Fig. 3. The results for the combination of internetworking, message delivery schemes (multicast and unicast) and PTP clock modes (end-to-end transparent clocks, or E2E-TP, peer-to-peer transparent clocks, or P2P-TC, and boundary clocks, or BC) are summarized in Table 3. When we apply unicast operation for P2P-TC and BC modes, the network is not operable since L2 switches with PTP only support a multicast address concerning the present standard. When we use PTP-implemented L2 switches associated with ordinary L3 switches, P2P-TC mode is not operable since Pdelay massages are discarded in the L3 switches. This is due to the regulation that the time to live (TTL) applies for Pdelay massages. It should be noted that the bidirectional IP multicast scheme, which is a relatively recent technology, should be implemented for the multicast operation in ordinary L3 networks. Although the PTP master-slave system is operable even in ordinary L2 and/or L3 networks alone, or networks without PTP-implemented L2 switches, as not shown in Table 3, the system may be severely affected by packet congestion and contentions at every switch to exhibit unsatisfactory synchronization errors.

A simple internetworking experiment was conducted as shown in Fig. 4. To configure Connection (a), which is a single PTP-implemented L2 network, the time synchronization error at the slave furthest from the master was tens of nanoseconds, regardless of the clock mode, E2E-TC, P2P-TC or BC, with the multicast operation, and of the traffic congestion with a background traffic load of 5 or 95%. Conversely, for Connection (b), where two PTP-implemented L2 networks operating in the unicast E2E-TC mode are interconnected by an ordinary L3 network in-between, the furthest slave clock exhibited that time synchronization errors were 10 and 24 μs for background traffic loads of 5 and 95% at the L3 link, respectively.

It should be noted that a much larger ordinary L3 network than Fig. 4 Connection (b) may exhibit unsatisfactory time synchronization errors for the WAMPAC system, exceeding the requirement, namely 50 μs. When we apply an ordinary L2 or L3 network with a link speed of 100 Mbps, the packet propagation time may fluctuate at each switch port by 6.72 and 123 μs due to the contention of packets of length 64 and 1,518 bytes, respectively.

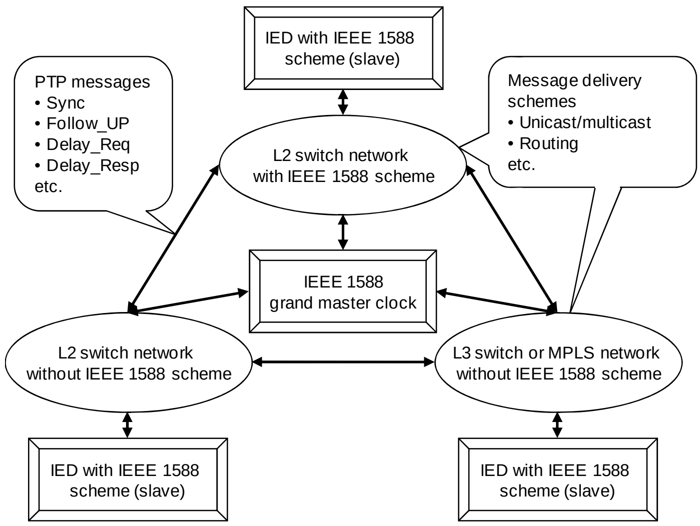


Fig. 3 Internetworking for PTP time synchronization

Table 3 Operability of the internetworking of ordinary networks with PTP-implemented L2 network

Combination of networks			Message delivery schemes and PTP clock modes					
			Unicast			Multicast		
L2 with PTP	Ordinary L2	Ordinary L3	E2E-TC	P2P-TC	BC	E2E-TC	P2P-TC	BC
X			✓	–	–	✓	✓	✓
X	X		✓	–	–	✓	✓	✓
X	X	X	✓	–	–	✓	–	✓
X		X	✓	–	–	✓	–	✓

Note: Symbols ✓and − represent correct and incorrect operations, respectively.

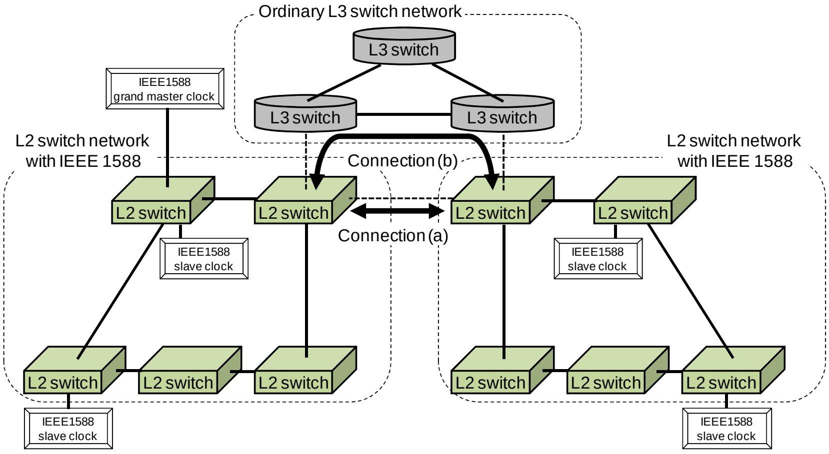


Fig. 4 Experimental configuration of PTP internetworking

B. Bidirectional IP multicast operation

The PTP time synchronization scheme and some WAMPAC applications need bidirectional multicast communications. To avoid the complexity of multiple setting of ordinary, or unidirectional, multicast protocol, Protocol Independent Multicast - Sparse Mode (PIM-SM), for bidirectional operation, a bidirectional IP multicast setting with bidirectional identical routes is available by using the Bidirectional PIM (BIDIR-PIM). The BIDIR-PIM operation for PTP time synchronization was examined in the network shown in Fig. 5, where the L3 and L2 switches were ordinary. The time synchronization scheme operated appropriately under the condition of non-traffic congestion to exhibit a time synchronization error of 1 to 2 µs. When a link failure (a cable disconnected manually) occurred, as shown in Fig. 5, the network was switched within 3 seconds or so and momentarily exhibited a time synchronization error of 32.8 µs. When the link failure recovered, the network was switched back immediately within 140 ms, much less than a PTP message cycle of 1 s, and showed no increase in time synchronization errors. If the free running performance of the slave device (IED/PMU) is enhanced, the time synchronization errors during network failure and subsequent switchover may be reduced, while the pull-in time may be longer.

C. MPLS network with unicast operation

When we applied ordinary L3 switch networks for PTP time synchronization, there were cases where the in- and out-bound communication routes differed physically because the routing protocol, Open Shortest Path First (OSPF), identifies multiple routes at the same cost. Since the route cost is usually determined solely by the number of L3 switches and the link speeds in the route, routes with different propagation lengths and/or different vendors' switches may involve the same cost, but different propagation times, leading to time synchronization errors. Through MPLS traffic engineering, we can designate the same route for both in- and out-bound paths. An experiment using an MPLS network with unicast operation for PTP time synchronization showed time synchronization errors similar to ordinary L2 switch networks.

3.2 Prototype WMPAC System and Operation Performance

The prototype WAMPAC system consists of a personal computer as a platform for the CE and WAMPAC-GW, and four IEDs with integrated PMU functions (IED/PMUs) as illustrated in Figure 6. The WAMPAC-GW and IED/PMUs are interconnected by L2/L3 networks, the communication specifications of which are defined in Table 4. The target power system is

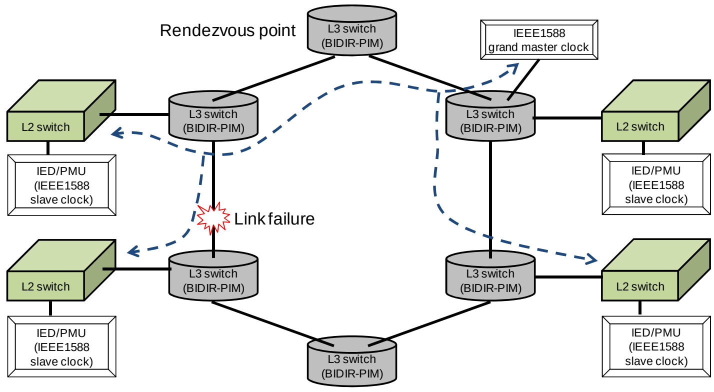


Fig. 5 Experimental configuration of bidirectional IP multicast operation

simulated using RTDS®. The international standards applied to this system are (1) IEC 61970 for the communications interface between the WAMPAC-GW and CE, (2) IEC 61850-1 to -10 and -90-5 for communication between the WAMPAC-GW and IED/PMUs, (3) IEEE C37.118.1 for phasor measurement in IED/PMUs, (4) PTP E2E-TC for time synchronization in L2 switches and IED/PMUs, and (5) BIDIR-PMI for IP multicast in L3 switches and IED/PMUs.

The total system operating time required is less than 250 ms from fault occurrence to generator tripping. We determined the operating time from fault occurrence to tripping as less than 150 ms together with satisfactory communication and time synchronization performance.

4. Conclusions

In this paper, based on the WAMPAC system architecture, the communication network specifications in terms of function, performance, reliability and cyber security were defined. The time synchronization characteristics were also examined for L2/L3 switches with or without PTP schemes implemented as well as multicast/unicast operations in IEDs to show a satisfactory synchronization error of a few microseconds. We established a prototype WAMPAC system comprising four IEDs, and determined the operating time from fault occurrence to tripping to be less than 150 ms. The communication specifications proposed above should desirably be incorporated in international standards or technical documents.

Acknowledgements

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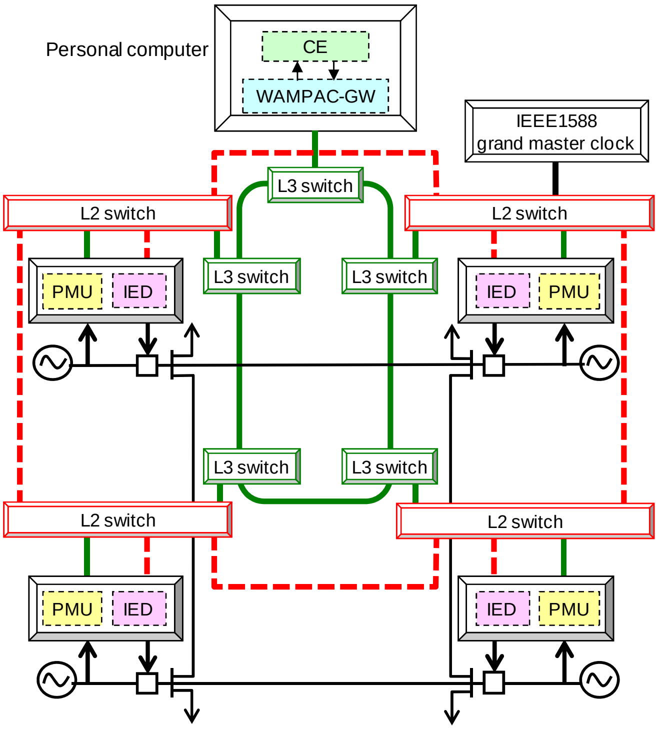

Fig. 6 Configuration of the prototype WAMPAC system

Table 4 Communication specifications for the prototype WAMPAC system

Transmission delay between IED and WAMPAC-GW	≤ 10 ms
Transmission delay between IEDs	≤ 10 ms
Communication rate of IED and PMU	Twice per electrical cycle
Bandwidth	400 kbps per IED/PMU
Time synchronization error among IED/PMUs	< 50 μs

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